

**Environmental Technology  
Verification Program**  
Advanced Monitoring  
Systems Center

Generic Verification Protocol  
for On-Board  
Vehicle Emission Monitors

ET ✓ ET ✓ ET ✓

**GENERIC VERIFICATION PROTOCOL**

**FOR**

**ON-BOARD VEHICLE EMISSION MONITORS**

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## ACRONYMS

<b>AMS</b>	Advanced Monitoring Systems
<b>CFR</b>	Code of Federal Regulations
<b>CH<sub>4</sub></b>	methane
<b>CL</b>	chemiluminescence
<b>CO</b>	carbon monoxide
<b>CO<sub>2</sub></b>	carbon dioxide
<b>EPA</b>	United States Environmental Protection Agency
<b>ETV</b>	Environmental Technology Verification
<b>FTP</b>	Federal Test Procedure
<b>GC</b>	gas chromatography
<b>g/mi</b>	grams per mile
<b>FID</b>	flame ionization detector
<b>LDV</b>	light-duty vehicle
<b>LRB</b>	laboratory record book
<b>mph</b>	miles per hour
<b>NDIR</b>	non-dispersive infrared spectrometry
<b>NMHC</b>	non-methane hydrocarbons
<b>NO<sub>x</sub></b>	nitrogen oxide
<b>OBD</b>	on-board diagnostic
<b>OEM</b>	on-board emission monitor
<b>O<sub>2</sub></b>	oxygen
<b>QA</b>	quality assurance
<b>QC</b>	quality control
<b>QMP</b>	quality management plan
<b>rpm</b>	revolutions per minute
<b>THC</b>	total hydrocarbons
<b>TSA</b>	technical systems audit

# **1 INTRODUCTION**

## **1.1 Environmental Technology Verification Background**

This protocol provides generic procedures for implementing a verification test of monitors that continuously measure the concentration of various gaseous components of vehicle emissions under normal operating conditions (i.e., on-road driving) and may provide quantitative vehicle emissions data (e.g., g/mi emission rates) based on live engine data scanning. The verification test is conducted under the auspices of the U.S. Environmental Protection Agency (EPA) through its Environmental Technology Verification (ETV) program. The purpose of the ETV program is to provide objective and quality-assured performance data on environmental technologies, so that users, developers, regulators, and consultants can make informed decisions about these technologies. ETV verification does not imply approval, certification, or designation by EPA, but rather provides a quantitative assessment of the performance of a technology under specified test conditions.

The verification tests are coordinated by Battelle, of Columbus, Ohio, which is EPA's partner in the ETV Advanced Monitoring Systems (AMS) Center. The scope of the AMS Center covers verification of monitoring technologies for contaminants and natural species in air, water, and soil. In performing verification tests, Battelle follows the procedures specified in this protocol and complies with the data quality requirements in the "Quality Management Plan for the ETV Advanced Monitoring Systems Pilot" (QMP).<sup>(1)</sup>

## **1.2 Test Objective**

The purpose of verification tests of on-board vehicle emission monitors (OEMs) is to evaluate their performance under realistic operating conditions. Specifically, these monitors are evaluated by comparisons with chassis dynamometer test results to assess accuracy and reproducibility and through operation during normal on-road driving to assess performance under realistic conditions. The effect of temperature on the performance of the OEMs is assessed by varying the dynamometer cell conditions under which selected tests are performed. The

unit-to-unit reproducibility of the OEM is evaluated from comparisons between duplicate monitors during both the dynamometer tests and the on-road driving tests. General performance characteristics of these OEMs, such as reliability and ease of use, also are evaluated through observations by the test personnel.

### **1.3 Test Applicability**

This generic protocol is applicable to the verification testing of vehicle emission monitors that can be operated on board a vehicle under normal driving conditions. The OEMs to be tested are capable of providing real-time concentration measurements of several key pollutants in vehicle exhaust and, in some cases, quantitative emission rates (e.g., g/mi), as calculated from the concentration measurements and live engine parameter data. In accordance with the intent of the ETV program, the OEMs to be tested are commercially available and not developmental products or prototypes.

## **2 TECHNOLOGY DESCRIPTION**

This document details the procedures for the verification testing of technologies that can be mounted in a variety of light- or heavy-duty vehicles and are capable of monitoring emissions from these vehicles under routine driving conditions. These OEMs are portable, weighing up to approximately 60 pounds, and can be installed in the passenger seat or trunk of most vehicles without modifying the vehicle. The OEMs can measure exhaust emissions of vehicles during their regular operation. In some cases, the OEMs also simultaneously collect live engine data from vehicles equipped with on-board diagnostic (OBD) ports to monitor fuel consumption, as well as operating characteristics of the vehicles. These OEMs use the live engine data to determine real-time emission rates.

The basic component of the OEMs to be tested in a verification test is a multi-gas analyzer for measuring the composition of the vehicle exhaust. Additionally, these OEMs may include other components such as a laptop computer to collect, process, and store data or an engine diagnostic scanner to monitor engine data. For those OEMs with engine scanning capabilities, the computer uses live engine data to compute exhaust mass flow, which, when

multiplied by the measured concentrations of exhaust gases, yields grams per second data. Grams per mile emissions are then calculated from the vehicle speed and time data.

The primary components of the OEMs are contained in a single case, which can be installed in the passenger seat of most domestic cars and trucks. The OEMs are designed for automatic operation so that no user attention is needed during operation.

### **3 VERIFICATION APPROACH**

#### **3.1 Scope of Testing**

The objective of the verification test derived from this generic protocol is to evaluate the performance of OEMs under realistic operating conditions. It is not the intent of this test to determine emissions data for the vehicles used in the test. Rather, the intent is to establish the performance capabilities of these OEMs under normal driving conditions (i.e., on the road), as well as in standard vehicle test cycles using dynamometers. To achieve this goal, this verification test involves two phases. The first phase of testing involves comparing the OEMs and the current standard for vehicle emissions monitoring, namely dynamometer testing. The second phase of verification involves performance evaluation of the OEMs during on-road testing. In all tests, two duplicate units of each OEM are operated side by side.

#### **3.2 Experimental Design**

This section describes the experimental design for an OEM verification test. The approach is based on the primary objectives of this test: to assess the overall accuracy (i.e., bias and precision) of an OEM relative to a chassis dynamometer and to assess OEM performance under real-world conditions. The approach to the verification test is summarized below, and the statistical methodology for establishing bias and precision are described in Section 6.2.

For this test, three gasoline-powered light-duty vehicles (LDV) shall be recruited by the test facility for both chassis dynamometer testing and road testing. The vehicles shall be chosen to include current models of vehicles that are popular in the on-road fleet. Furthermore, the vehicles shall be chosen by the test facility to include a wide range of emission rates and engine

sizes (i.e., 4, 6, 8 cylinder). The vehicles also shall be chosen to assure that both the mass flow and speed density methods used by the engine diagnostic system to determine exhaust mass are included in the test.

To establish intra-method precision (i.e., unit-to-unit relative error), it is necessary to include duplicate OEMs as part of the study design (see Section 6.2). This approach is analogous to the use of collocated monitors for establishing the precision of ambient air monitoring sampling and analytical techniques. Duplicate OEMs are operated in both phases of the verification test.

In the first phase of the verification test, the vehicles are operated on a chassis dynamometer, and the vehicle emissions are monitored by both the OEMs being verified and by laboratory reference methods. Given the goal of evaluating OEM performance under real-world conditions, it is important to perform an array of dynamometer test runs. Consequently, the vehicles are each operated on two test cycles: the Federal Test Procedure (FTP),<sup>(2)</sup> and the US06<sup>(2)</sup> cycle. The use of different vehicle emission rates, along with the different test cycles, provides a range of real-world conditions under which bias and precision results are to be obtained.

Three runs under each test scenario (i.e., under each test cycle and vehicle combination) are conducted. There are two important reasons for including multiple runs in the design of the test. First, multiple runs provide information on test-to-test repeatability. Such data are essential for establishing the reliability of the reference method results, which are treated as the “truth” or “gold standard” to which OEM results are to be compared. Second, triplicate runs allow for statistically testing whether or not interactions between vehicle type and test cycle have an impact on observed bias and precision. For example, it may be the case that levels of bias and/or precision differ from vehicle to vehicle, but only when the FTP test cycle is run and not the US06. As another example, one vehicle type may show consistent bias and precision across both test cycles, while the other two vary in bias and precision depending on the test cycle. Without multiple runs, the statistical significance of such interaction cannot be determined.

A summary of the dynamometer runs that are performed in this verification test is provided in Table 1.

**Table 1. Summary of Chassis Dynamometer Runs**

Test cycle	Vehicle 1	Vehicle 2	Vehicle 3	Total
<b>FTP<sup>a</sup></b>	3	3	3	9
<b>US06</b>	3	3	3	9
<b>Total</b>	6	6	6	18

<sup>a</sup> FTP produces multiple bags, so more than 18 observations will be obtained for bag-level calculations.

After the dynamometer runs shown in Table 1 are completed, a series of four US06 test cycles is performed on the vehicle with mid-range emissions. In this series, a single US06 dynamometer run is performed with the vehicle accessories off at each of three different temperatures (i.e., 30°F, 75°F, and 100°F). The fourth US06 run is performed at 100°F with the vehicle's air conditioner operating at maximum capacity to assess whether use of the vehicle's accessories influences the performance of the OEMs.

For all the dynamometer runs, the test facility shall measure vehicle emissions by the reference methods described in Section 3.3. The results obtained from these reference methods are used as the basis of comparison for establishing bias. During each dynamometer run, the vehicle emissions are monitored in real time by the reference methods and by the duplicate OEMs, for total hydrocarbons (THCs), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and nitrogen oxides (NO<sub>x</sub>). Methane is monitored by the reference method at the bag level and used to determine non-methane hydrocarbons (NMHCs) as needed. Bias and precision are determined independently for each of these analytes. The performance of the two duplicate OEMs is based on comparisons between the test level results (e.g., average concentration or g/mi) from each of the duplicate OEMs and the results from the reference methods. These comparisons are made primarily on the test level, but also on the per-bag level (e.g., the three bags comprising the FTP schedule). Graphic comparisons of the second-by-second data are used as a secondary comparison to illustrate the transient response of the OEMs.

In the second phase, duplicate on-board monitors shall be installed in a test vehicle; and the vehicle shall be driven over two different routes for at least 15 minutes each. The two routes shall be different in nature with one including predominantly stop-and-go traffic and the other including predominantly sustained high-speed traffic. While the test vehicle is driven over these

two routes, second-by-second data are collected by the duplicate on-board emission monitors. Results from the duplicate monitors are compared to establish the unit-to-unit reproducibility of the OEMs being verified.

Furthermore, general issues of performance, including reliability and ease of use, are assessed based on observations recorded during the verification test and reported for the OEMs, in addition to the overall cost of the monitors.

### **3.3 Reference Methods**

During a verification test, various analytical methods shall be used by the test facility to measure the concentrations of THC, methane (CH<sub>4</sub>), CO, CO<sub>2</sub>, and NO<sub>x</sub> in vehicle emissions. THC concentrations are measured using a flame ionization detector (FID), CH<sub>4</sub> is determined using gas chromatography (GC) with FID, CO and CO<sub>2</sub> concentrations are determined by non-dispersive infrared spectroscopy (NDIR), and NO<sub>x</sub> concentrations will be measured using a chemiluminescence (CL) analyzer. These methods are described in 40 Code of Federal Regulations (CFR) Part 86<sup>(2)</sup> and shall be the reference methods for this verification test. Results from these methods serve as the basis of comparison for evaluating the accuracy of the on-board emission monitor. These analyses, with the exception of CH<sub>4</sub>, are performed both in real time and on collected bag samples. CH<sub>4</sub> is determined only by analysis of collected bag samples. NMHC concentrations are deduced from the difference between the bag sample THC and CH<sub>4</sub> readings.

### **3.4 Test Facility**

The test facility to be used for a verification test of on-board vehicle emission monitors should be a recognized emissions testing laboratory, with facilities appropriate for chassis dynamometer testing according to 40 CFR Part 86. The test facility shall have standard operating procedures in place for the dynamometer runs and laboratory analyses to be performed in this verification and shall have trained personnel capable of performing these activities according to those standard procedures. Documentation of the staff qualifications shall be provided to Battelle in the form of training records prior to test initiation.

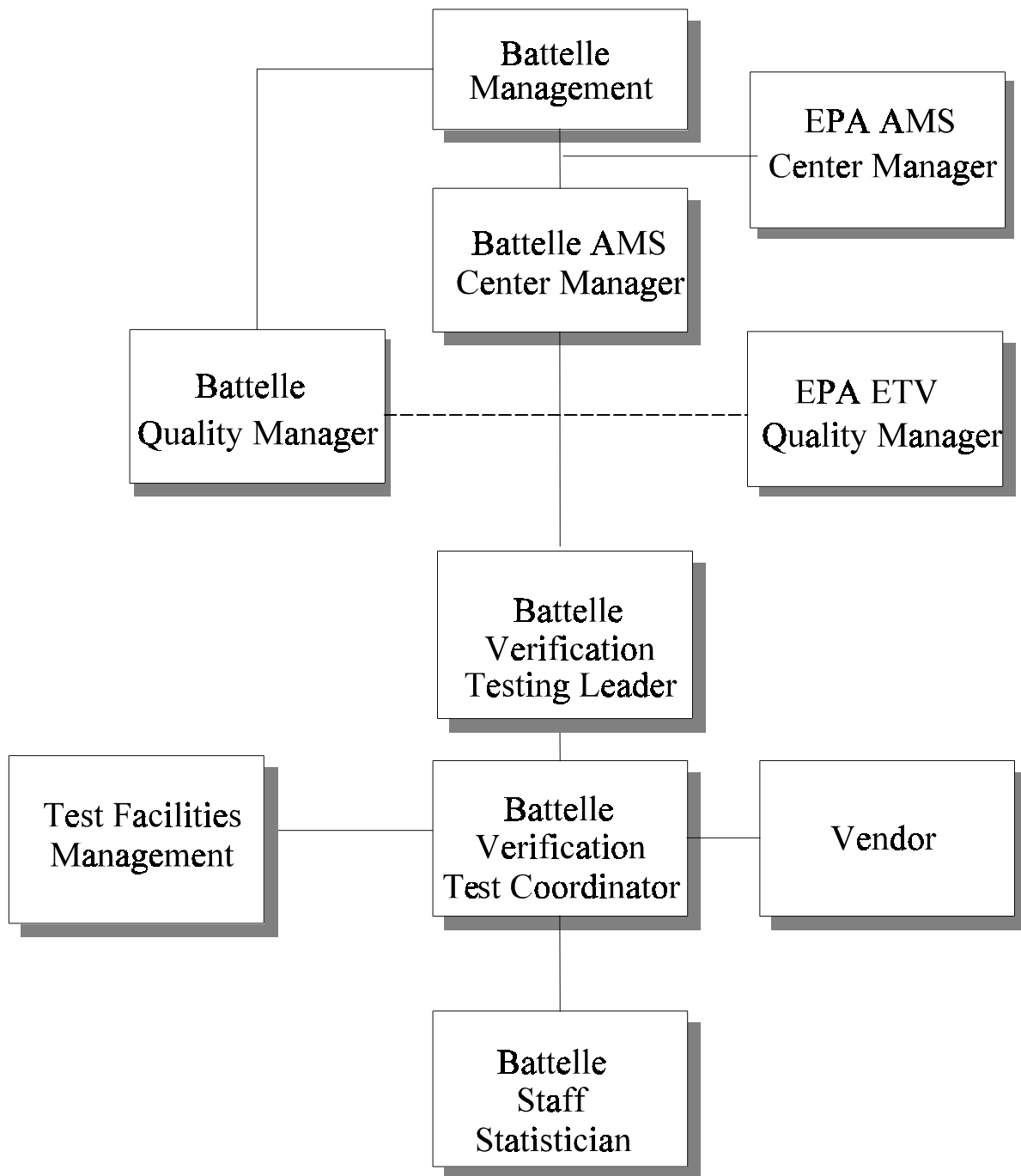
### **3.5 Roles and Responsibilities**

The verification test is coordinated and supervised by Battelle personnel and conducted at a recognized test facility with documented quality assurance (QA) procedures in place. Staff from the test facility participate in this test by operating the dynamometer and providing the reference measurements. Vendor representatives install, maintain, and operate their respective technologies throughout the test. QA oversight is provided by the Battelle Quality Manager, and, at his/her discretion, the EPA ETV Quality Manager. The chart in Figure 1 shows the organization of responsibilities for Battelle, the vendor companies, EPA, and the test facility. Specific responsibilities are detailed below.

#### **3.5.1 Battelle**

The Verification Test Coordinator has the overall responsibility for ensuring that the technical, schedule, and cost goals established for the verification test are met. The Verification Test Coordinator shall

- Prepare a draft test/QA plan, verification reports, and verification statements
- Revise the draft test/QA plan, verification reports, and verification statements in response to the reviewers' comments
- Coordinate testing at the testing site
- Ensure that all quality procedures specified in the test/QA plan and in the QMP are followed
- Respond to any issues raised in assessment reports and audits, including instituting corrective action as necessary
- Serve as the primary point of contact for vendor and test facility representatives
- Establish a budget for the verification test and monitor staff effort to ensure that the budget is not exceeded



**Figure 1. Organization Chart for On-Board Vehicle Emission Monitor Verification Test**

- Coordinate distribution of the final test/QA plan, verification reports, and verification statements
- Ensure that confidentiality of vendor information is maintained.

The Verification Testing Leader for the AMS Center provides technical guidance and oversees various stages of the verification test and shall

- Support the Verification Test Coordinator in preparing the test/QA plan and organizing the testing
- Review the draft test/QA plan
- Review the draft verification reports and statements
- Ensure that confidentiality of vendor information is maintained.

Battelle's AMS Center Manager shall

- Review the draft test/QA plan
- Review the draft verification reports and statements
- Ensure that necessary Battelle resources, including staff and facilities, are committed to the verification test
- Ensure that vendor confidentiality is maintained
- Support the Verification Test Coordinator in responding to any issues raised in assessment reports and audits
- Maintain communication with EPA's AMS Center and ETV Quality Managers.

Battelle shall provide a Staff Statistician, who supports statistical and data analysis activities for this verification test. As needed, the Staff Statistician shall

- Assist in converting verification data from electronic spreadsheet format to appropriate file format for statistical evaluation
- Support the Verification Test Coordinator in performing statistical calculations specified in the test/QA plan on the verification data

- Provide results of statistical calculations and associated discussion for the verification reports
- Support the Verification Test Coordinator in responding to any issues raised in assessment reports and audits related to statistics and data reduction.

Battelle's Quality Manager for this verification test shall

- Review the draft test/QA plan
- Conduct a technical systems audit (TSA) once during the verification test
- Audit at least 10% of the verification data
- Prepare and distribute an assessment report for each audit
- Verify implementation of any necessary corrective action
- Issue a stop work order if self-audits indicate that data quality is being compromised; notify the Battelle AMS Center Manager if a stop work order is issued
- Provide a summary of the audit activities and results for the verification reports
- Review the draft verification reports and statements
- Have overall responsibility for ensuring that the test/QA plan and QMP are followed
- Ensure that Battelle management is informed if persistent quality problems are not corrected
- Interface with the EPA ETV Quality Manager.

### **3.5.2 Vendors**

Vendor representatives shall

- Review the draft test/QA plan and provide comments and recommendations
- Approve the revised test/QA plan
- Work with Battelle to commit to a specific schedule for the verification test
- Provide duplicate commercial-ready monitors for testing

- Provide an on-site operator(s) throughout the verification test period to install the monitors in the test vehicles and operate and maintain the monitors during testing
- Remove monitors and other related equipment from the test facility upon completion of the verification test
- Review and comment upon their respective draft verification reports and statements.

### **3.5.3 EPA**

EPA's responsibilities in the AMS Center are based on the requirements stated in the "Environmental Technology Verification Program Quality and Management Plan for the Pilot Period (1995-2000)"<sup>(3)</sup> or the most current update of this document. The roles of the specific EPA staff are as follows.

EPA's ETV Quality Manager shall

- Review the draft test/QA plan
- Perform, at his/her option, one external TSA during the verification test
- Notify the Battelle AMS Center Manager to facilitate a stop work order if an external audit indicates that data quality is being compromised
- Prepare and distribute an assessment report summarizing the results of an external audit, if performed
- Review draft verification reports and statements.

EPA's AMS Center Manager shall

- Review the draft test/QA plan
- Approve the final test/QA plan
- Approve the final verification reports
- Review the draft verification statements.

### **3.5.4 Test Facility**

The responsibilities of the test facility are to

- Assist in developing the test/QA plan for the verification test
- Allow facility access to vendor, Battelle, and EPA representatives during the scheduled verification test, including set-up and tear-down operations
- Select, secure, and operate vehicles for the dynamometer and road testing
- Perform all reference emissions measurements
- Provide all test data to Battelle electronically, in mutually agreed upon format
- Assist vendor in installing the OEMs in the test vehicles
- Perform dynamometer runs and associated vehicle preconditioning according to the procedures and schedule described in this test/QA plan
- Provide EPA and Battelle staff access to and /or copies of appropriate QA documentation of test equipment and procedures
- Assist in Battelle's reporting of the test facility's QA/quality control (QC) procedures
- Review portions of the verification report to assure accurate descriptions of the test facility operations and to provide technical insight on verification results
- Provide safety instructions to test and QA personnel for operations at the test facility.

## **4 TEST PROCEDURES**

### **4.1 Vehicle Recruitment and Inspection**

Three gasoline-fueled vehicles shall be recruited and inspected by the test facility to ensure suitability for use in the verification test. The test vehicles should include currently popular models that are representative of the on-road fleet. The vehicles should be in good working condition; however, at least one should be a high exhaust emitter, based on the experience of the test facility. The recruited vehicles must have on-board diagnostic ports that

are compatible with the OEMs being tested and should be capable of providing data sufficient to determine vehicle speed in miles per hour (mph), engine speed in revolutions per minute (rpm), and engine torque (or its surrogate). The identification number for each vehicle shall be recorded by Battelle staff in a laboratory record book (LRB), in addition to a general description of the vehicle (i.e., make, model, year, etc.).

The vehicles shall be inspected for fuel and exhaust leaks by the test facility prior to testing. Any required vehicle repairs are documented in the LRB.

## **4.2 Monitor Installation**

The on-board emission monitors to be verified shall be installed by a vendor representative, who ensures that each monitor is calibrated and operating properly before testing begins on each day of testing. The duplicate OEMs are installed with appropriate plumbing to split the exhaust stream for analysis by the on-board emissions monitors and by the test facility. A leak check shall be performed before road testing and each series of dynamometer runs to ensure the integrity of the exhaust sampling assembly. Any observed leaks shall be repaired before testing begins. The vehicle battery shall be used to power one of the two OEMs, and a secondary supply (independent of the vehicle battery) shall be used to power the other OEM.

The installation activities (including on-site calibration, repairs, etc.) shall be documented by Battelle staff in the LRB. Observations regarding installation time and simplicity, ease of use, practicality, passenger safety, etc., in the verification report shall be based on the installation of a single unit.

## **4.3 Dynamometer Testing**

Dynamometer runs are performed according to the schedule shown in Table 2 and conducted with the vehicle accessories off, except where noted. The test facility shall document the run conditions, which are to be in accordance with 40 CFR Part 86. This documentation shall be provided to Battelle.

**Table 2. Schedule for Dynamometer Runs**

<b>Day 1</b>	<b>Day 2</b>	<b>Day 3</b>	<b>Day 4</b>
Vehicle 1 - FTP	Vehicle 1 - FTP	Vehicle 1 - FTP	Vehicle 2 - US06 @ 30°F
Vehicle 1 - US06	Vehicle 1 - US06	Vehicle 1 - US06	Vehicle 2 - US06 @ 75°F
Vehicle 2 - FTP	Vehicle 2 - FTP	Vehicle 2 - FTP	Vehicle 2 - US06 @ 100°F
Vehicle 2 - US06	Vehicle 2 - US06	Vehicle 2 - US06	Vehicle 2 - US06 w/AC
Vehicle 3 - FTP	Vehicle 3 - FTP	Vehicle 3 - FTP	
Vehicle 3 - US06	Vehicle 3 - US06	Vehicle 3 - US06	

Because this test is not designed to determine emission rates for the test vehicles, strict adherence to the soak and preconditioning procedures described in 40 CFR Part 86 is not necessary. However, conditions should be consistent for replicate runs of each test cycle. After the vehicle soak (12 to 36 hours), the test vehicle should be placed on the dynamometer and prepared for testing. An FTP cycle is performed with the intent of immediately performing a US06 cycle within 10 minutes of completing the FTP test. If the US06 cycle is not started within 10 minutes of completion of the previous cycle, the first 505 seconds of the FTP driving cycle is performed to condition the vehicle. Alternate FTP and US06 cycles are performed in sequence on the three vehicles on each of three test days. On the fourth day of testing, a series of three US06 test cycles should be performed, including one at each of the following temperatures: 30°F, 75°F, and 100°F. These tests are conducted using the vehicle with the mid-range emissions as established by the previous testing. After this sequence of temperature tests, an additional US06 cycle is performed at 100°F with the vehicle's air conditioner operating at maximum capacity.

For each driving cycle, the exhaust emissions and engine activity data are monitored by both the test facility reference methods and the duplicate OEMs. The test facility shall record and report the data on THC, CH<sub>4</sub>, CO, CO<sub>2</sub>, and NO<sub>x</sub> emissions at the test, bag, and second-by-second level. Similarly, the OEM records THC/NMHC, CO, CO<sub>2</sub>, NO<sub>x</sub>, and oxygen (O<sub>2</sub>) at the test, bag, and second-by-second level. Summaries of the second-by-second values are compared with the corresponding bag values to assess agreement for the reference measurements of CO<sub>2</sub>, NO<sub>x</sub>, and THC. Agreement between the two values should be within 5.0%, 10%, and 15%,

respectively. Tests not meeting these criteria should be reviewed as to their validity or impact on the verification results and repeated if possible and if necessary.

#### **4.4 Road Testing**

Each of the three test vehicles used in the dynamometer tests described above shall be driven on two separate routes over public roads while the duplicate OEMs record second-by-second data for THC/NMHC, CO, CO<sub>2</sub>, O<sub>2</sub>, and NO<sub>x</sub>. Engine data are recorded either by the OEMs being tested or by a laptop computer. Weather conditions and observations concerning traffic and vehicle operation are recorded in a LRB by the vehicle operator. The vehicles should begin the road testing with a full tank of suitable locally available gasoline and shall complete the two driving routes in succession (i.e., on the same trip). The routes to be driven should be such that they include the following conditions:

- a) at least 15 minutes of stop-and-go traffic through a central business district
- b) at least 15 minutes of sustained high-speed driving on a freeway.

Test routes should be consistent from vehicle to vehicle and from test to test (i.e., different OEM verification tests). An effort should be made to conduct testing under similar driving conditions (i.e., time of day, weather conditions) for the verification tests of different OEMs.

### **5 QUALITY ASSURANCE/QUALITY CONTROL**

#### **5.1 Calibration**

The dynamometer and laboratory instrumentation to be used in this verification test shall be calibrated by the test facility according to the standard operating procedures and schedules in place at the test facility. These calibration specifications must meet or exceed those described in 40 CFR 86.<sup>2</sup> Documentation of these calibrations are provided to Battelle by the test facility prior to test initiation.

If not required by the reference methods or by the standard operating procedures of the test facility, calibration verifications of specific instrumentation are performed at the request of Battelle during the verification test. The results of the calibration verifications shall be provided to Battelle.

## **5.2 Audits**

Independent of test facility and EPA QA activities, Battelle is responsible for ensuring that the following audits are conducted as part of this verification test.

### **5.2.1 Pre-Test Facility Audit**

At least two weeks prior to verification testing, the Verification Test Coordinator and/or the Battelle Quality Manager may conduct an audit of the test facility chosen to conduct the verification test. If performed, this audit is conducted to ensure that the test facility has the equipment necessary to perform the verification test and that a satisfactory QA/QC program is implemented at the test facility. The audit should include at least a tour of the dynamometer facilities and review of appropriate standard operating procedures and calibration records. If possible, the audit should also include observation of on-going dynamometer testing.

### **5.2.2 Technical Systems Audits**

Battelle's Quality Manager shall perform a TSA at least once during the verification test. The purpose of this audit is to ensure that the verification test is being performed in accordance with the AMS Center QMP<sup>(1)</sup>, this protocol, referenced methods, and any standard operating procedures used by the test facility. During this audit, the Battelle Quality Manager reviews the reference methods used, compares actual test procedures to those specified or referenced in this protocol, and reviews data acquisition and handling procedures. This effort includes reviewing the actual procedures used at the test facility for compliance with this test/QA plan and with the standard operating procedures for the test facility. A TSA report shall be prepared, including a

statement of findings and the actions taken to address any adverse findings. The EPA ETV Quality Manager shall receive a copy of Battelle's TSA report.

At EPA's discretion, the EPA ETV Quality Manager also may conduct an independent TSA of the verification testing procedures.

### **5.2.3 Performance Evaluation Audits**

A performance evaluation audit shall be conducted to assess the quality of the reference measurements made in the verification test. This audit should address only the emissions measurements provided by the reference methods. The audit is performed by analyzing a National Institute of Standards and Technology (NIST)-traceable calibration gas standard that is independent of those used by the test facility during the testing. The acceptance criteria for the results of this audit are identical to those already in place at the test facility for calibration verification. This audit is performed once during the verification test.

### **5.2.4 Audits of Data Quality**

Battelle's Quality Manager shall audit at least 10% of the verification data acquired during the verification test. The Battelle Quality Manager traces the data from initial acquisition, through reduction and statistical comparisons, to final reporting. All calculations performed on the data undergoing the audit are checked.

## **5.3 Reporting**

Each audit shall be documented in accordance with the AMS Center QMP.<sup>(1)</sup> Audit reports include the following:

- Identification of any adverse findings or potential problems
- Corrective actions that address adverse findings or potential problems

- Confirmation by Battelle's Quality Manager that the corrective actions have been implemented and are effective
- Citation of any noteworthy practices that may be of use to others.

All audit reports are reviewed by the AMS Center Manager and Verification Testing Leader. A copy is sent to the EPA ETV Quality Manager and the EPA AMS Center Manager.

#### **5.4 Corrective Action**

The Battelle or EPA ETV Quality Manager, during the course of any audit, shall identify to the technical staff performing experimental activities any immediate corrective action that should be taken. If serious quality problems exist, the Battelle Quality Manager is authorized to stop work. Once the audit report has been prepared, the Verification Test Coordinator ensures that a response is provided for each adverse finding or potential problem and implements any necessary follow-up corrective action. The Battelle Quality Manager shall ensure that follow-up corrective action has been taken.

### **6 DATA HANDLING AND REPORTING**

#### **6.1 Data Review**

Data generated by the test facility and vendors in the verification test shall be provided to Battelle and are reviewed by the Verification Test Coordinator before they are used to calculate, evaluate, or report verification results. These data include electronic data, entries in laboratory record books, operating data from the test facility, and equipment calibration records. The review is documented by the person performing the review by adding his/her initials and date to a hard copy of the record being reviewed. This hard copy is placed in the files of this verification test by the Verification Test Coordinator.

In addition, data calculations performed by Battelle shall be spot-checked by Battelle technical staff to ensure that calculations are performed correctly. Calculations to be checked

include determination of accuracy, intra-method precision, and other statistical calculations as identified in Section 6.2 of this protocol.

## 6.2 Statistical Calculations

Performance verification is based, in part, on statistical comparisons of the average concentration results or g/mi results from the on-board emission monitor to results from the reference methods. A summary of the calculations to be made is given below.

### 6.2.1 Bias

The bias of each of the duplicate OEMs is assessed at the test level based on the percent difference between the average concentration measurements or the g/mi emission rates from the OEM relative to the reference method. For each individual dynamometer run, the percent difference,  $d_i$ , between the OEM and the reference method results is calculated as

$$d_i = \frac{Y_i - X_i}{X_i} \times 100 \quad (1)$$

where  $Y_i$  represents the test level results from the OEM, and  $X_i$  represents the test level results of the reference method for a given analyte. The average,  $D$ , and standard deviation,  $s$ , of these individual bias results is calculated from

$$D = \frac{\sum_{i=1}^n d_i}{n} \quad (2)$$

and,

$$s = \sqrt{\frac{\left( \sum_{i=1}^n d_i^2 \right) - (nD^2)}{n-1}} \quad (3)$$

where  $n$  is the total number of dynamometer runs. The standard deviation and average difference are used to calculate the upper,  $UL$ , and lower,  $LL$ , 95% confidence limits for the bias of each monitor according to:

$$UL = D + t_{0.975}(s) \quad (4)$$

and

$$LL = D - t_{0.975}(s) \quad (5)$$

where  $t_{0.975}$  is the 0.975 quantile of the Student's  $t$  distribution with  $n-1$  degrees of freedom. Bias is calculated independently for each of the duplicate monitors and each analyte. Additionally, bias is calculated independently for each vehicle and for each test cycle (i.e., FTP, US06).

### 6.2.2 Precision

Intra-method precision is calculated based on the percent difference in the readings of the duplicate monitors relative to the mean of the readings, as shown below:

$$d'_i = \frac{Y'_i - Y_i}{(Y'_i + Y_i) / 2} \times 100 \quad (6)$$

where  $Y_i$  and  $Y'_i$  are the test level results for a given analyte from the two duplicate monitors for each test cycle  $i$ . The coefficient of variation,  $CV_i$ , for each dynamometer run and vehicle is calculated according to Equation (7).

$$CV_i = \left| \frac{d'_i}{\sqrt{2}} \right| \quad (7)$$

The individual coefficients of variation for all test cycles and vehicles are pooled according to Equation (8) to determine the overall precision of the monitors.

$$CV = \sqrt{\frac{\sum_{i=1}^n (CV_i)^2}{n}} \quad (8)$$

The upper,  $UL$ , and lower,  $LL$ , 90% confidence limits for the monitor's CV are given by

$$LL = CV \sqrt{\frac{n}{\chi_{0.95,n}^2}} \quad (9)$$

and

$$UL = CV \sqrt{\frac{n}{\chi_{0.05,n}^2}} \quad (10)$$

where  $n$  is the number of degrees of freedom, and  $\chi_{0.95,n}^2$  and  $\chi_{0.05,n}^2$  are the 0.95 and 0.05 quantiles, respectively, of the  $\chi^2$  distribution with  $n$  degrees of freedom. Precision is assessed independently for each analyte, as well as for each vehicle and each test cycle.

Supplemental comparisons are made at the second-by-second level to determine the instantaneous unit-to-unit reproducibility of the duplicate monitors. As with the test level results, these comparisons are made based on a percent difference calculation.

### 6.2.3 Other Comparisons

Second-by-second data from the OBD port and the OEM shall be compared graphically to illustrate temporal correlations between the vehicle operational parameters and the measured components in the vehicle exhaust. Likewise, second-by-second data from the reference analyzers are compared visually against those from the OEM to illustrate temporal correlations. No statistical evaluations are made of these second-by-second comparisons owing to likely differences in the lag times and response times between the reference analyzers and the OEMs.

For the on-road tests, second-by-second comparisons are made between the results of the duplicate monitors.

### **6.3 Reporting**

The statistical comparisons that result from each of the tests described above shall be conducted separately for each of the two units of each technology being verified, and information on the additional performance parameters are compiled and reported. Separate verification reports are then prepared, each addressing a technology provided by one commercial vendor. Each report shows separate verification results from the two units undergoing testing, along with calculations of the unit-to-unit reproducibility of the technology. For each test conducted in the verification, the verification report presents the test procedures and test data, as well as the results of the statistical evaluation of those data.

The verification report shall briefly describe the ETV program, the AMS Center, and the procedures used in verification testing. These sections will be common to each verification report resulting from this verification test. The results of the verification test shall then be stated quantitatively, without comparison to any other technology tested or comment on the acceptability of the technology's performance. The preparation of draft verification reports, review of reports by vendors and others, revision of the reports, final approval, and distribution of the reports shall be conducted as stated in the "Generic Verification Protocol for the Advanced Monitoring Systems Pilot."<sup>(4)</sup> Preparation, approval, and use of verification statements summarizing the results of this test also are subject to the requirements of that same protocol.

## **7 HEALTH AND SAFETY**

The test facility shall provide appropriate safety instructions regarding potential hazards during the verification testing to Battelle and vendor staff. The OEMs shall be installed and operated so that the OEM operators or the drivers of the vehicles are not endangered, nor is the

integrity of the test vehicle compromised. Testing performed on the road shall be conducted in accordance with local traffic laws and speed restrictions.

## **8 REFERENCES**

1. “Quality Management Plan for the ETV Advanced Monitoring Systems Center,” U.S. EPA, Environmental Technology Verification Program, Battelle, Columbus, Ohio, December 2001.
2. “Control of Air Pollution from New and In-Use Motor Vehicles and New and In-Use Motor Vehicle Engines: Certification and Test Procedures,” U.S. EPA 40 CFR Part 86.
3. “Environmental Technology Verification Program Quality and Management Plan for the Pilot Period (1995-2000),” U.S. EPA, EPA-600/R-98/064, Cincinnati, Ohio, May 1998.
4. “Generic Verification Protocol for the Advanced Monitoring Systems Pilot,” U.S. EPA, Environmental Technology Verification Program, Battelle, Columbus, Ohio, October 1998.